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The Use of Mammals As Sentinels for Human Exposure to Toxic Contaminants in the Environment

by Daniel J. O'Brien,[1] John B. Kaneene,[1] and Robert H. Poppenga[2]

The use of sentinel species shows the potential to bridge the gap between animal-based and human-based environmental health research. With regard to the assessment of environmental contamination, the use of the terms "indicator," "monitor," and "sentinel" has often been confusing and ambiguous. A set of definitions is proposed as a standard to rectify this situation. The advantages of the use of sentinel species are provided, as well as criteria for sentinel selection, based on species characteristics. The recent use of mammals as sentinels for human exposure to toxic environmental contaminants is reviewed. A tabulated review of mammals proposed as indicators or monitors is included, as these may act as a database for the selection of sentinel species for future research efforts. The complexity and subtlety of factors interacting between an organism and its environment make it imperative that one provide a focused definition of what one wants the sentinel to assess and for what particular aspect of human health. Some examples of how sentinels might be selected for particular research questions are provided. While the potential for sentinel use in the field of environmental health is enormous, future investigators need to choose sentinels carefully, based on well-defined research questions, and confine conclusions drawn to the particular problem the sentinel was chosen to assess.

Introduction

Contamination of the environment with toxins of anthropogenic origin has now reached the level where it has become a concern, and it has been recognized as such (*1*). Attempts to quantify or assess the impact of contamination often focus either on individual nonhuman species of interest or on humans alone. The scientific literature is full of examples of the former, and while these are considered important to people interested in the welfare of particular species, the human population tends to be unconcerned unless it is shown that its own health is directly threatened. Human subjects may provide the most relevant source of information on contamination levels, biological effects, and possible dangers to human health, but several factors, such as the lack of the ability to sample sufficient quantities of tissues (*2*) and human activities that confound interpretation of population-based studies (*3*), can complicate the ease with which conclusions are reached. Moreover, purely human studies do not take into account the threats to the other organisms that share man's environment. The use of sentinel species shows the potential to bridge the gap between these two paths of research. We will review how others have used some sentinel species, assess some factors by which their use can be compared and evaluated, and give examples of how some species may be suited for future research into levels of environmental contamination and their threat to human and animal health. We will confine our scope to the usage of mammals for these purposes.

Some Definitions: What Do We Mean by a Sentinel?

As one reads through the scientific literature on environmental contamination, the confusing and often ambiguous use of the terms "monitor," "indicator," and "sentinel" becomes apparent. This fact has been pointed out by other authors (*4*). The three terms have been used interchangeably, or in various combinations that blur or disregard any distinctions between them (*5–7*). The terms "tool for tracking" (*8*) and "biological barometers" (*9*) have also been used to refer to mammalian species that might be used to assess environmental contamination. A standard set of definitions would seem appropriate to aid in the interpretation of existing literature and to clarify new information generated in this growing area. In this light, we propose a system of nomenclature based on the work of previous authors, modified where necessary, with some appropriate generalizations.

The Oxford English Dictionary (OED) (*10*) defines an indicator as "one who or that which points out or directs attention to something," and more specifically, as "a group of animals whose

[1]Population Medicine Center, Michigan State University, A-109 Veterinary Medical Center, East Lansing, MI 48824-1314.

[2]Department of Pathology, Michigan State University, East Lansing, MI 48824-1316.

Address reprint requests to D. J. O'Brien, Population Medicine Center, Michigan State University, A-109 Veterinary Medical Center, East Lansing, MI 48824-1314.

presence acts as a sign of particular environmental conditions." This suggests the fact that indicators point out the discrete quality of a particular factor or characteristic being present or absent, but do not quantify it in any way (*4*). When one uses the term, then, it is necessary to state what particular situation or attribute is being indicated. In our context, to refer to a particular species as an indicator and not specify of what seems inappropriate. Although the term bioindicator has been referred to as estimating (i.e., quantifying) the level of environmental contamination (*11*), perhaps the best definition is that of Landres et al. (*12*), upon which we base our definition:

> *Indicators:* organisms whose characteristics are used to point out the presence or absence of environmental conditions which cannot be feasibly measured for other species or the environment as a whole.

The rationale, uses, and limitations of indicator species have been discussed succinctly by Steele and co-workers (*13*).

The term "monitor" extends the indicator concept. The OED specifies a monitor as "something that reminds or gives warning" (*14*). Rather than merely pointing out presence or absence, a monitor gives a way to evaluate the extent of something over time, to quantify it to the point where conclusions can be drawn. Martin and Coughtrey (*4*) extensively explain the distinction between indicators and monitors, and give the criteria by which distinctions may be made. Considered as a subgroup of biological indicator, Newman (*15*) defines monitors as "bioassay monitors," i.e., a "species with known life histories and known characteristic responses to a given air pollutant." These attributes can be extended to other forms of environmental contamination as well. Thus, our definition:

> *Monitors:* organisms in which changes in known characteristics can be measured to assess the extent of environmental contamination so that conclusions on the health implications for other species or the environment as a whole can be drawn.

The concept of a sentinel species, our object of interest here, extends and refines the monitor a step further. Here, the OED defines the role of acting as a sentinel as "to stand guard over; keeping watch" (*16*). Newman (*15*) points out a key characteristic of sentinels, that they act as early warning signals of contamination. We propose that the use of the term sentinel be restricted to species that can act as early warning indicators which specifically delineate implications or dangers to the health of humans. Our definition then:

> *Sentinels:* organisms in which changes in known characteristics can be measured to assess the extent of environmental contamination and its implications for human health and to provide early warning of those implications.

It should be noted that, in the sense described here, sentinels are a distinct subgroup of monitors, which are distinct subgroups of indicators. In the environmental sense they all describe change, but in specifically different ways.

In summary, indicators point out the discrete presence or absence of particular environmental conditions. Monitors allow the graded evaluation and quantification of the degree of particular environmental conditions. Sentinels allow graded evaluation and quantification with specific and exclusive reference to implications for human health, and give early warning of those implications. The distinctions, though subtle, are quite significant.

Our attention will be directed toward sentinels. The other two categories will be considered here only in the narrow sense in which they apply to sentinels.

Why Sentinels?

As pointed out in the Introduction, the most direct and relevant way to study the levels and health effects of environmental contaminants in humans would be to use humans themselves as research subjects. For a number of reasons this is not always possible. The first obvious reason is the inavailability of tissues for study. Sentinels have the potential to provide much more comprehensive information on tissue distribution of toxicants and pathological effects. For example, to collect samples of brain tissue for analysis from children to study ambient lead levels would not be appropriate or feasible for obvious ethical reasons, but such information could be obtained with an appropriate sentinel organism. In addition, sentinels may develop clinical signs more rapidly after exposure (*17*), thus providing the requisite "early warning" of threat to human health (*9,18,19*). With regard to population-based studies, sentinel animals do not share some of man's behaviors (e.g., smoking, occupational [workplace] exposure) which can act as confounding factors in study interpretation (*3*).

Although the majority of the literature on the effects of toxic environmental contamination and levels in the environment comes from analytical chemical studies and laboratory based studies using laboratory animal species, there are inherent limitations in the types of conclusions that can be drawn from them. In analytical chemical studies, environmental samples obtained for analysis do not necessarily mirror actual environmental contamination, nor do they take the unique susceptibilities of man or particular animals into consideration (*20*). Though no one would question the value of laboratory toxicity tests, extrapolation of results to man or other species in the field can prove problematic due to the interplay of the many subtle, unidentified factors operating in the environment (*21,22*). Sentinels can help to overcome both of these drawbacks. Sentinel species are also useful as a means of gathering medical data that may be relevant to similar diseases in humans. The utility of making certain diseases in sentinel species reportable to public health authorities has been reported (*9,23*) as such a means. Finally, and perhaps most importantly, sentinels perform the function of calling attention to the interrelationship between human health and animal health with respect to the environment, providing a way to justify the expense of obtaining information on animal species by showing its implications for humans.

However, a number of areas of potential difficulty exist in implementing the sentinel concept. First, the sentinel is probably not suitable for application on a global or country-wide basis, since the variability of species and environmental characteristics between regions is often marked. In addition, the subpopulations of humans that the sentinel guards will vary substantially from place to place and culture to culture. As we will see, the sentinel is a tool for specific rather than for generalized application. The availability of biological samples from the chosen species presents another potential problem. This could largely depend

on the nature of the biological effect being considered as an early warning sign. If the effect of interest necessitates obtaining organs or body fluids for analysis on a frequent basis, the utility of a sentinel would be limited to species that could be sampled at the specified times. On the other hand, if the contaminant of interest produced an obvious or characteristic clinical sign, such as a change in behavior, more specific biological sampling could be postponed until this clinical sign became evident. A number of species are managed in such a way as to make this sampling possible. Livestock species are often slaughtered at specific points in their life cycle. Many wildlife species that are sufficiently abundant in a given area are harvested periodically through hunting and trapping. Companion animals (e.g., dogs and cats) under the care of animal control agencies due to abandonment, nuisance complaints, etc., could be sampled if the desired samples for analysis could be obtained noninvasively (hair, blood, feces, etc.). Similar samples could be obtained from pet animals with owner permission and cooperation by veterinarians. Finally, species endangered or threatened within a given area obviously could not be used, but wildlife species extirpated from one area are often abundant in another and would be subject to population control, making sampling possible. All of these problem areas need to be carefully and critically evaluated in conjunction with other criteria when selecting a sentinel species.

Some Criteria for a Good Sentinel

Several references exist that give criteria for selection of indicator and monitor species (*4,24–26*). Landres et al. (*12*) do an admirable job pointing out the difficulties in selection, and Holden (*27*) has analyzed the various pitfalls and difficulties involved in the use of monitors on a global basis. Many of these criteria also broadly apply to the selection of sentinel species, and we propose our criteria list as a digest of applicable characteristics from these authors and our own observations.

It should be noted that these criteria need to be considered as a continuum, not as a list that any proposed sentinel must fulfill in its entirety. Indeed, it is very unlikely that any species would meet all of these criteria without some area of weakness, and the relative strengths and weaknesses of a species need to be considered in the context of the study situation to which its application is intended.

Inherent Criteria

Size. One of the most basic factors for consideration of sentinel species is how large or small they are. A sentinel needs to be large enough to provide adequate tissue samples for analysis of the toxicant under study.

Sensitivity. The proposed sentinel must be sensitive enough to be predictive of human exposure and its routes, and its reaction needs to be specific to the particular agent. Although some authors have demonstrated that a sentinel less sensitive than humans can be useful in pointing out an existing intoxication problem in humans (*28*), it would probably be of greater utility to choose a sentinel more sensitive to a particular toxin than its guarded human group. In this way, one might expect clinical signs in the sentinel before their appearance in man, fulfilling the aforementioned "early warning" function.

Physiological Characteristics. Three key factors are necessary in regard to physiological characteristics. First, with regard to the toxicant in question, the sentinel needs to be similar enough to man physiologically to show comparable biological and pathological effects following exposure. Second, baseline parameters of the sentinel's physiology need to be known or have the potential to be feasibly determined so that "normal" characteristics can act as a standard to measure changes against. Third, the organism must accumulate the toxicant to levels that reflect environmental concentrations. Sentinel levels need to change in direct proportion to changes in the environment.

Longevity. The sentinel should have a life span long enough to demonstrate the effects of exposure over time so that conclusions can be drawn concerning the consequences of chronic exposure and concerning any variability of effects for different age groups.

Latent Periods. The time span between initial exposure to a toxic agent and the appearance of biological effects or clinical signs should ideally be short, so that early warning of subsequent effects of chronic exposure in humans could be identified. In addition, a short latent period might allow better assessment of the length and course of the intoxication.

External Factors

Position in the Food Chain (Food Web). Humans, under normal circumstances, are omnivores at the top trophic level of the food chain. In order to be comparable, a sentinel would ideally also be omnivorous and at the top of its food chain. Exceptions to this might be in cases where human exposure to a particular toxicant is primarily through a specific food source, such as meat or fish, in which case a strict carnivore or piscivore would be appropriate. An intermediate position in the food chain has been advocated as desirable by Hernandez et al. (*29*), but the advantages of this position are unclear. Finally, an additional position for a sentinel would be as a food source for humans. This would give toxic levels in these organisms considerable public health implications because of the tendency of some toxicants to accumulate or biomagnify up food chains and because contaminated food has been a source of human toxic exposure in the past (*30,31*).

Migration. Although the use of widely migratory mammals to monitor toxic contamination over vast areas such as oceans has been suggested (*32*), for an ideal sentinel species, migrations would be limited or absent. Human populations of interest occupy rather discrete geographic areas, and assuming one is interested in the risk to humans from contamination in that area, the sentinel would need to be sedentary within it as well. If one measures elevated tissue levels of a toxicant in an animal that migrates between areas, one cannot say for sure where exposure occurred, whereas if high levels are detected in a sedentary species, exposure would necessarily have occurred within a known area.

Route of Toxic Exposure Similar to Humans. Route of exposure is essentially a further specification of the idea that sentinels need to "share the same environment as man." Routes of intoxication must be identified and standardized to determine risk from environmental contamination and to predict biological and pathological consequences (because these can vary widely according to exposure route for a given toxicant).

Abundance and Distribution. Sentinels need to be abundant enough to make statistically significant sampling logistically

feasible. Moreover, it is important that the sentinel species chosen will not be adversely effected by the removal of individuals for sampling purposes. For this reason, the use of endangered species or species whose populations are depleted or unstable within a study area would not be appropriate. Some have suggested the use of "nuisance" species, whose thriving populations already need to be managed on a continuing basis by trapping and removal (*5*). Such species could provide an abundant sampling source. In addition, the ideal sentinel should be widely distributed within the area to be assessed, so that levels in the organism are representative of the entire area of concern.

Ability to Propagate in Captivity. Although our concern is mainly with environmental field studies where the application of data from laboratory studies can prove problematic (as previously noted), there are unquestionably some parameters that are best assessed in a laboratory setting (e.g., baseline physiological parameters) where better control of variables is possible. With this in mind, the ability to reproduce and maintain populations of a sentinel species in captivity would be desirable. Such a characteristic would allow both laboratory and field studies to be conducted on the same species and the results compared. Variable forces at work in the environment might be identified and assessed in this manner. Large mammals may not be suitable for laboratory studies (*33*) due to the expense and logistical difficulties of maintaining and propagating them in captivity.

Other Factors

Multiple Species. Buck (*20*) has pointed out the importance of using more than one species simultaneously to adequately monitor environmental quality. This may apply to sentinels as well. While individual species have unique characteristics that make them suitable as sentinels, their differing responses when simultaneously exposed to a similarly contaminated environment may help to elaborate subtle influences that could have implications for human health. Simultaneous use will not only allow critical comparison of sentinel species, but also contribute to the taxonomic breadth of the conclusions drawn concerning the ways in which human and animal health are interrelated.

Goal Definition. Although the primary purpose of sentinels is to guard human health, selection of sentinels should also take into consideration what can be accomplished on a long-term basis. Ideally, they can offer a means to measure progress in environmental health and to define goals which may benefit both themselves and humans (*34*).

Review of the Literature

The number of studies in which mammals have been used to assess the risks of toxic environmental contamination in humans is fairly limited; fewer than 20 studies have simultaneously looked at levels and effects of toxicants in both humans and their sentinels. A number of these studies have investigated the possible uses of sentinels to assess risks to humans of neoplasia secondary to toxic exposure from the environment. The majority of these studies have focused on dogs. Hayes and Mason (*35*) reviewed the use of a number of domestic animals as sentinels of human disease in general, including health problems related to toxicants. Citing their epidemiological work with pet dogs (*19*), they proposed the use of dogs as sentinels for human bladder cancer. These workers calculated proportional morbidity ratios for various types of cancer diagnosed in dogs at 13 veterinary referral hospitals in the United States and Canada and related them to an estimate of the level of industrialization in the surrounding counties. These were then compared with age-adjusted mortality rates from bladder cancer in whites from the same counties surrounding the veterinary referral centers and their relationship to the level of industrialization. They found a significant positive correlation between bladder cancer and level of industrialization in both dogs and humans.

In two other studies, Hayes concentrated on canine bladder cancer specifically with respect to etiologic factors that might be similar between humans and dogs (*23*) and then examined the comparative epidemiological features of various neoplasms in dogs and cats and related them to similar cancers in humans, with an eye toward using these pets as prognostic sentinels (*36*). In the former study, transitional cell carcinoma was focused on, as this neoplasm was seen to evolve from environmental exposure in humans (*37*). Relation of these cancers to urine-borne carcinogens was theorized in both humans and dogs, and the absence of smoking and occupational exposure risks in dogs was cited as further support for the dog as a sentinel species.

The use of the dog as a sentinel for environmentally related neoplasia in the humans was also proposed by Glickman and coworkers in two separate studies (*14,38*). In the former, the use of dogs as sentinels for human exposure to asbestos was proposed, and dogs diagnosed with mesothelioma were examined to determine environmental risk factors that might be associated with asbestos-related diseases in their owners. Glickman et al. significantly associated canine mesothelioma with owners' asbestos-related occupations or hobbies and the use of flea repellents on the dogs. In the latter study, again using bladder cancer as the biological effect, the authors examined the use of household dogs to determine carcinogens in insecticides and proposed their potential use to assess adverse effects in humans.

The other cancer-related use of sentinel species involved domestic sheep. Newell and co-workers (*39*) examined the influence of some environmental factors on the prevalence rate of small intestinal adenocarcinoma in sheep. They found significant increases in tumor rate associated with exposure to phenoxy and picolinic acid herbicides and significantly larger increases associated with how recently food stuffs were sprayed with these herbicides before consumption (i.e., the more recent sprayings were associated with larger increases in tumor rate). The authors were appropriately cautious not to claim their findings as an analogy for disease in humans. They made the captivating observations that *a*) the prevalence rates of human colonic carcinoma and sheep small intestinal adenocarcinoma in New Zealand are both among the highest in the world, *b*) the sheep small intestine and human colon are similar in many respects, and *c*) New Zealand is among the major users of phenoxy and picolinic acid herbicides in the world. In light of their findings in sheep, the potential role of the sheep as a sentinel species in this situation is obvious.

Finally, a brief review on the value of domestic animals in the evaluation of the environmental causes of cancer has been offered (*40*), recognizing veterinary epidemiology as an underexploited resource in human disease investigation.

Sentinels have also been used to identify environmental teratogens and to compare rates of birth defects in mammals and humans (*41*). Marienfeld proposed and used domestic swine as his sentinel species and gathered information on birth defects by questionnaires from 40,000 swine producers over a 3-year period. Although no conclusions could be drawn concerning the implications for humans (as no statistical comparisons were performed), the study indicated the possibility of relating levels of teratology to geographic area and using domestic animals as sentinels.

A number of other studies have investigated the potential role of sentinels to monitor or assess health effects in humans from exposure to various toxic agents in the environment. The majority of these studies concern the heavy metals lead and mercury. Thomas and his co-workers (*28*) proposed and used family dogs from 83 low-income families to assess and predict the prevalence of higher-than-normal blood lead concentrations in children from the same families. They concluded that the discovery of an abnormally high blood lead concentration in a family dog increased the probability of finding a child in the same family with abnormally high blood lead 6-fold. They also pointed out the remarkable similarity between lead intoxication in young dogs and children with regard to socioeconomic status, area of residence, season, source of lead, and biological effects. On the average, blood lead concentrations tended to be higher in children than in dogs from the same family, calling into question whether the dogs were sensitive enough to provide early warning. However, in another study of 389 dogs from four sites with various levels of environmental lead contamination (lead mining, lead smelting, urban and rural island), the authors concluded that dogs were more sensitive than children and that elevated lead levels in dogs should be viewed as early warning of risk to children (*42*). They found the highest lead concentrations in the mining site, and blood lead concentrations were significantly affected by location (mining > smelting > urban > rural island). Though they appeared clinically normal, more than 10% of the dogs from the mining and smelting sites had blood lead levels that exceeded concentrations considered diagnostic for lead poisoning, compared to 4% of children at the smelting site.

With regard to mercury, the classic documentation of both human and animal poisonings concerned the tragic contaminations at Minamata and Niigata, Japan. The interested reader is referred to the comprehensive literature available about this outbreak (*43,44*), which will not be discussed here. Pet cats were proposed as sentinels and used to study the clinical and pathological effects of organic mercury poisoning by Takeuchi and co-workers (*18*). They looked at two cats that developed neurological signs after eating fish from a methylmercury-contaminated river system in Ontario. These animals showed similar clinical signs, mercury levels, and histopathological effects as domestic cats poisoned at Minamata. The authors ominously pointed out that the cats at Minamata had exhibited these same signs just before the onset of massive human morbidity from methylmercury intoxication and inferred the gravity of the possible health consequences for the humans living near and eating fish from the contaminated river. They cited work that showed some of these individuals had indeed developed clinical signs characteristic of methylmercury poisoning.

Smith and Armstrong (*45*) examined mercury concentrations in various food items for a group of native Inuit in Northern Canada. Though the region is far from industrial sources of mercury contamination, humans here had above average (though not dangerous) blood mercury levels, which were thought to be due to eating contaminated seal meat and liver. While the humans' diet was presumed to be sufficiently varied to avoid intoxication, it was noted that sled dogs owned by the Inuit and fed a nearly exclusive diet of seal had much higher mercury levels in their livers. It was suggested that these dogs could act as sentinels to predict what human levels might approach if seasonal population constraints of their other primary food items (caribou and char) forced the Inuit to consume seal as a greater proportion of their diets.

Pet animals have also been studied as sentinels for health effects that might be due to environmental contamination with polychlorinated biphenyls (PCBs) and 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD). Schilling and co-workers (*17*) concluded that dogs could serve as sentinels for human exposure to PCB. These authors measured serum PCB levels in dogs living near sites of PCB contamination. Relative to controls, they found PCB exposures in dogs were greater in areas where the soil was known to be contaminated with PCB. Humans occupying these same contaminated areas also manifested elevated PCB levels in their sera, and at levels higher than the subject sentinel dogs. Unfortunately, no PCB levels were determined for adipose tissues where these lipophilic compounds accumulate. Due to clearance by hepatic and other tissues, serum does not accurately reflect body burdens of PCBs, and so the author's conclusions may not be accurate.

Another study used questionnaire data on family dogs and cats in an attempt to assess their potential use as sentinels for human health risks from environmental contamination with waste oils containing TCDD (*46*). Although small samples, owner recall bias, and the inability to confirm owner-reported sickness with veterinary medical records prevented them from extrapolating sentinel results to humans, these authors' findings suggested dogs and cats in TCDD-contaminated areas may have greater health risks than nonexposed pets. Notably, they also cautioned against reliance on owner reports in future research on the use of sentinels in environmental health.

Finally, a few case reports with implications for sentinel use also appear in the literature. While these were not studies where a sentinel was proposed and then used, the fact that animals became sick and were closely followed by humans after exposure to the same toxic agent illustrates nicely the concept of the sentinel as an early warning guard of human populations. The first such incident occurred in 1971, when waste oil contaminated with TCDD was sprayed on the riding arena of a horse breeding farm for dust control purposes (*47*). Within 3 days of application, birds nesting in the arena rafters were found dead, and over the succeeding weeks and months, rodents, cats, dogs, and horses died after exposure to the arena. A 6-year-old child who played in the arena soil later developed hemorrhagic cystitis and pyelonephritis, and two other exposed children developed skin lesions consistent with chloracne. The arena soil was found to contain approximately 32 ppm TCDD.

A second incident concerned a group of farmers who obtained waste grain that had been treated with organomercurial fungicide and incorporated it into feed for their hogs (*29*). Feeding of this grain began in late August, and 2 or 3 weeks later one hog was slaughtered and consumed over the next 3.5 months. By October, 14 of the hogs had developed neurological

signs, and 12 of 14 died within 3 weeks. In December, three family members who had consumed the butchered hog became sick. Organomercurial poisoning was diagnosed and confirmed by analysis of the tissues of various hogs and of human serum, urine, and cerebrospinal fluid. Placental transfer from mother to a child born after exposure was noted as well.

The third episode, far from being an isolated incident of contamination, reached the scope of a true agricultural disaster (*48*). The fire retardant polybrominated biphenyl (PBB) was mistaken for a feed additive with a similar tradename and incorporated into livestock feeds. In a matter of weeks, cattle became sick and died. Subsequently, various human illnesses that were linked to exposure to contaminated animal products were reported, although it is important to point out that public health officials were not able to attribute any human illness to exposure. In one study of human populations, 70% of the control group had detectable blood levels of PBB. As a result nearly 30,000 cattle, 6,000 swine, and 1,500 sheep were quarantined and destroyed, and the effects in humans are still being debated.

Indicators and Monitors

In marked contrast to actual sentinel studies, the number of publications devoted to the proposal or use of mammals as indicators or monitors is extensive. While the contrast of these animals from sentinels has already been elaborated, indicator and monitor studies may, nevertheless, provide a database from which organisms may be selected for use as possible sentinels in future research efforts. A general review of the use of domestic animals has been published (*20*), and Wren (*49*) has reviewed mammalian monitors for heavy metals. An impressive review and evaluation of the use of small mammals has recently been published as well (*50*); other mammals suggested or used as indicators or monitors are presented in Tables 1 and 2, respectively. In a few instances, we have included citations where suitability was determined from context rather than stated. Suggestion as an indicator or monitor here does not imply whether or not the animal was considered a good or poor monitor/indicator.

Conclusions

The myriad factors interacting between an organism and its environment necessarily make the assessment and evaluation of environmental health a complex undertaking at best. The attempt to precisely define particular aspects to investigate seems well advised. This is particularly true with respect to the use of sentinels for human disease. As we have already seen, the definition and use of sentinel mammals has often been ambiguous. While the potential for the use of sentinels of environmental contamination threats to man seems nearly unlimited, it is imperative to provide a focused definition of what one wants the sentinel to assess and for what particular aspect of human health. This needs to be established for a given situation before selecting a sentinel species. In this light, it seems pointless to postulate any "best" species of mammals for use as sentinels; this is most appropriately left to individual investigators to determine on a case-by-case basis in future research. However, we can give a few examples of how sentinels might be chosen for particular research questions. Obviously, these are not meant to cover all the possible criteria for every situation, only to illuminate the thought processes that contribute to sentinel selection.

Consideration of the source of a toxicant will be used as the first example. If the main human exposure is through ingestion in foodstuffs, one might consider the use of the animal that is the foodstuff, or of a species that ingests that particular foodstuff as a major portion of its diet. To assess human exposure to organochlorine pesticides with agricultural applications as a source, if the human exposure of interest was through pork, the pig could be evaluated as a sentinel, as it accumulates these pesticides while grazing (*51*). Dairy cattle or goats could be used if the source under study was milk products, as milk is a major excretory route for organochlorines in these animals (*52*).

Moreover, specific subpopulations with sources of exposure that larger populations do not commonly receive could possibly use the sentinel effectively. As an example, consider hunters who use their prey as a foodstuff. Within specific areas, hunting is a common pastime, and among hunters, organ meats are consumed along with carcass meat. In individuals who might be hunting for the purposes of subsistence, exposure to toxins present in organs of game animals could be significant. Cadmium, a known nephrotoxin (*53*), has been shown to accumulate in the organ meats of several game species that graze forages contaminated by atmospheric metal fallout, including red deer (*54*), moose, roe deer, and hares (*7*). Any of these species could be considered for use as a sentinel, depending on the chosen prey of the particular group of hunters being studied.

As a second example factor, the specific human physiological subgroup of interest must be considered before matching a sentinel to it. If considering effects of lead exposure on pregnant women, sheep might be selected because pregnant ewes are more susceptible to the effects of lead poisoning than nonpregnant sheep (*55,56*).

If the aim is to study specific biopathologic effects in humans, knowledge of similar specific effects in the sentinel would be valuable in addition to common sources of exposure. Consider lead intoxication in human children. Juvenile baboons (*Papio anubis*) are known to have symptoms and clinical progress which duplicate acute childhood lead poisoning (*57*), and, because it is a primate, the baboon's physiology would make it well suited to a sentinel role. In the wild, however, the baboon's utility would be limited to areas within countries where the species occurs, which might not be in the urban areas where most of the cases of childhood lead poisoning tend to occur. However, in the case of the dog, not only are clinical and kinetic aspects similar to children, morphologic tissue changes, age, season of occurrence, and hematologic and urinary findings are similar as well (*9,28*). The most common source of exposure for children (pica) is also the same in dogs (*58,59*). For this particular aspect of human lead poisoning, dogs would appear to be a more suitable sentinel.

Another example might concern human exposure to PCBs. An investigator interested in the effects of these toxins on pregnant women with contaminated fish as a source of exposure might consider the mink (*Mustela vison*) as a sentinel. Mink are known to be very sensitive to PCBs and to experience severe reproductive failure even at levels below 1 ppm of PCB in the diet (*60*) and when fed fish contaminated with PCB (*61*). A number of authors have also found significantly reduced growth rates in offspring of female mink exposed to dietary PCBs (*62,63*). Significantly decreased growth rates were documented in male children of women exposed to PCBs in contaminated cooking oil (*64,65*),

Table 1. Species proposed or used as indicators.

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Concentration, ppm Range	N	Reference
Order Artiodactyla	Germany, farm (contaminated by Pb	^{210}Pb	Liver	15.62 (± 11.52[a,b])	4.0 – 6.75	35	Bunzl et al., 1980 (*75*)
Family Bovidae			Kidney	20.68 (± 8.39)	8.4 – 42		
Cattle (*Bos taurus*)	mine)	^{210}Po	Liver	42.66 (±29.45)	13.9 – 159		
			Kidney	162.7 (±65.9)	57.8 – 387.8		
		Pb	Liver	1.34 (± 1.51)	0.2 – 6.2		
			Kidney	1.94 (± 1.80)	0.4 – 6.8		
	Italy, farm	Pb	Muscle	0.147 (± 0.116[b])	0.030 – 0.4	30	Amodio-Cocchieri and Fiore, 1987 (*76*)
			Milk	0.241 (± 0.049)	0.2 – 0.3	20	
			Liver	0.405 (± 0.365)	0.1 – 1.6	30	
			Kidney	0.573 (± 0.491)	0.2 – 2.6		
		Cd	Muscle	0.38 (± 0.020)	0.020 – 0.120	30	
			Milk	0.021 (± 0.002)	0.02 – 0.025	20	
			Liver	0.119 (± 0.081)	0.038 – 0.32		
			Kidney	0.342 (± 0.253)	0.060 – 0.9		
Sheep (*Ovis aries*)	Italy, farm	Pb	Muscle	0.226 (± 0.132)	0.05 – 0.4	30	Amodio-Cocchieri and Fiore, 1987 (*76*)
			Liver	0.537 (± 0.219)	0.3 – 0.88		
			Kidney	0.696 (± 0.361)	0.3 – 1.43		
		Cd	Muscle	0.178 (± 0.215)	0.035 – 0.690		
			Liver	0.219 (± 0.109)	0.058 – 0.390		
			Kidney	1.035 (± 1.005)	0.08 – 3.0		
Ibex[c] (*Capra ibex*)	Austria (some regions contaminated by air from steel and coal industry)	Pb				1	Köck et al., 1989 (*77*)
Family Cervidae	Quebec,[d] terrestrial	Cd	Liver	3.6 – 15.9	(M)[e]	431	Crête et al., 1987 (*78*)
Moose (*Alces alces*)				2.9 – 15.1	(F)		
			Kidney	38.9 – 73.1	(M)		
				31.8 – 100.0	(F)		
White-tailed deer (*Odocoileus virginianus*)			Liver	1.0 – 2.6	(M)		
				0.8 – 2.0	(F)		
			Kidney	21.1 – 39.0	(M)	7	Crête et al., 1987 (*78*)
				20.9	(F)		
	Central, S.E. Pennsylvania	Pb	Teeth	36.4	34.8 – 37.7	48	Witkowski et al., 1982 (*79*)
			Mandible	36.2	34.6 – 37.1		
Roe deer (*Capreolus capreolus*)	Poland, forest (air polluted)	Zn	Antler	1.32		79	Sawicki-Kapusta, 1979 (*11*)
		Pb		2.2			
		Fe		1.36			
		Cd		1.56			
		Cr		3.16			
	Austria	Cd	Liver	2.03[f]		52	Köck et al., 1989 (*70*)
		Pb		0.87			
	Germany (uncontaminated)	Pb	Liver	0.189		166	Hecht, 1984 (*80*)2
			Kidney	0.193		169	
			Diaphragm	0.109		134	
Red deer (*Cervus elaphus*)	Germany (uncontaminated)	Pb	Liver	0.329		107	
			Kidney	0.346		108	
			Diaphragm	0.089		96	
Family Suidae	Italy, farm	Pb	Muscle	0.19 (± 0.133)	0.04 – 0.5	30	Amodio-Cocchieri and Fiore, 1987 (*76*)
Pig (*Sus scrofa*)							
			Liver	0.357 (± 0.131)	0.2 – 0.6		
			Kidney	0.511 (± 0.258)	0.2 – 1.2		
		Cd	Muscle	0.048 (± 0.25)	0.01 – 0.095		
			Liver	0.199 (± 0.122)	0.066 – 0.5		
			Kidney	0.666 (± 0.536)	0.056 – 1.6		
Wild boar[c] (*Sus scrofa*)	Austria (as above)	Cd	Liver			1	Köck et al., 1989[c] (*70*)
		Pb					
Order Carnivora	Finland, freshwater lake	Hg	Muscle	36.76	0.7 – 196.9	7	Helminen et al., 1968 (*81*)
Suborder Pinnepedia							
Ringed seal (*Phoca hispida*)			Liver	73.85	2.4 – 209.8	6	
			Kidney	32.7	5.7 – 52.6	3	
Australian fur seal (*Arctocephalus pusillus*)	S.E. Australia, island, ocean	Hg	Muscle	0.91 (± 0.52)	0.09 – 1.90	16	Bacher, 1985 (*82*)
			Liver	62.3 (± 44.7)	0.97 – 170		
			Kidney	0.63 (± 0.43)	0.13 – 1.71		
			Spleen	1.29 (± 0.92)	ND – 3.80		
			Brain	0.70 (± 0.70)	ND – 2.53		

(Continued)

Table 1. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Concentration, ppm Range	N	Reference
			Hair[c]	9.59 (± 5.89)	1.07 – 19.8		
Northern fur seal (*Callorhinus ursinus*)	Alaska, island, open ocean	Aroclor 1254	Fat[b]	17.25		7	Kurtz and Kim, 1976 (*32*)
			Blood				
			Lice	1.45		5	
		Dieldrin	Fat	0.12		3	
			Blood	0.06		7	
			Lice				
		p,p'-DDTs	Fat	29.95		7	
			Blood	4.6		3	
			Lice	4.0		5	
Sea lion (*Zalophus californianus*)	California, island, ocean	Clophen A60 (PCB)	Liver[b]	3.0[g]		9	Bowes et al., 1973 (*83*)
			Blubber	62.0			
		DDE	Liver	12.0			
			Blubber	512.0			
Family Canidae Dog (*Canis familiaris*)	Boston, urban	Pb					Zook, 1973 (*9*)
Family Mustelidae Mink (*Mustela vison*)	Norway[d]	Hg	Liver[b]	2.6		71	Norrheim et al., 1984 (*84*)
	New England, farm (found dead)	DDT	Fat	1.59	0.25 – 4.0	5	Friedman et al., 1977 (*85*)
		DDE		0.99	0.1 – 2.0		
		Aroclor		29.2	6.0 – 60.0		
	Manitoba, river	Hg	Liver[b]	5.01	0.05 – 24.29	172	Kucera, 1983 (*86*)
			Kidney	3.68	0.06 – 23.5		
			Brain	1.68	0.05 – 19.69		
	Ontario, lake watersheds	Hg	Liver	1.55	ND – 7.5	91	Wren et al., 1986 (*87*)
			Kidney	1.76	0.13 – 5.54	68	
			Muscle	0.96	ND – 4.08	50	
			Brain	0.48	0.28 – 0.44	9	
River otter (*Lutra canadensis*)	Manitoba, river	Hg	Liver	6.25	1.27 – 21.65	36	Kucera, 1983 (*86*)
			Kidney	3.95	0.03 – 15.07		
			Brain	1.59	0.04 – 9.49		
	Alberta, stream and lake, forested	HCB	Liver[b]	0.003	0.001 – 0.02	44	Somers et al., 1987 (*88*)
			Lipid	0.003	0.006 – 0.097	58	
		α-BHC	Liver	0.01	ND – 0.002	44	
			Lipid	0.19	ND – 0.06	58	
		DDE	Liver	0.0023	ND – 0.23	44	
			Lipid	0.0083	ND – 0.158	58	
		DDD	Liver		ND – 0.005	14	
			Lipid				
		Chlordane, oxy	Liver	0.0015	ND – 0.008	44	
			Lipid				
		Chlordane, *cis*	Liver	Trace	ND – 0.006	38	
			Lipid				
		HE	Liver	0.001	ND – 0.003	44	
			Lipid				
		Dieldrin	Liver	Trace	ND – 0.001	30	
			Lipid				
		PCB	Liver	0.0165	ND – 0.084	44	
			Lipid	0.376	ND – 2.34	58	
	Ontario, lake watersheds	Hg	Liver	1.95	ND – 17.4	76	Wren et al., 1986 (*87*)
			Kidney	1.83	0.05 – 12.6	54	
			Muscle	0.74	0.07 – 4.26	48	
			Brain	1.04	0.16 – 7.15	10	
Family Procyonidae Raccoon (*Procyon lotor*)	S.E. United States, riparian	Organochlorines ^{137}Cs, ^{90}Sr, Hg					Bigler et al., 1975 (*5*)
	Connecticut[d]	Pb	Liver[b]	6.2 (±5.4)	<1.0 – 35	14	Diters and Neilsen, 1978 (*89*)
	Florida, tidal, island, urban	α-BHC	Fat	0.17		1	Nalley et al., 1975 (*90*)
		β-BHC		0.43	0.1 – 2.3	15	
		δ-BHC		0.05	0.02 – 0.12	5	
		Aldrin		0.07	0.03 – 0.09	5	

(Continued)

Table 1. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Range	*N*	Reference
		Dieldrin		0.29	0.02 – 2.3	17	
		OE		0.73	0.08 – 4.61	19	
		HE		0.23	0.02 – 1.53	17	
		o,p'-DDT		0.31	0.04 – 1.53	17	
		o,p'-DDE		0.09		1	
		o,p'-DDD		0.06		1	
		p,p'-DDT		0.49	0.04 – 3.25	17	
		p,p'-DDE		0.74	0.06 – 3.30	20	
		p,p'-DDD		0.14	0.03 – 0.25	7	
		Methoxychlor		4.63	0.16 – 36.82	10	
	Louisiana[d]	Chlordane-A		0.017			Dowd et al., 1985 (*91*)
		Chlordane-G		0.017			
		Toxaphene		0.095			
Family Ursidae Polar bear (*Ursus maritimus*)	Canada, arctic	Hg	Hair	0.095	1.1 – 44.3	109	Eaton and Farant, 1982 (*92*)
Order Cetacea Striped dolphin (*Stenella coeruleoalba*)	Japan, Pacific coast, pelagic waters	Cd	Muscle	0.10 (± 0.06)		59	Honda and Tatsukawa, 1983 (*93*)
			Pancreas	1.43 (± 0.42)		14	
			Lung	0.42 (± 0.10)		15	
			Heart	0.17 (± 0.08)		15	
			Spleen	0.55 (± 0.19)		12	
			Large intestine	0.46 (± 0.17)		15	
			Stomach, 1st	0.44 (± 0.35)		15	
			Stomach, 2nd	1.03 (± 0.67)		14	
			Diaphragm	0.12 (± 0.06)		15	
			Liver	6.26 (± 2.31)		31	
			Kidney	26.4 (± 16.2)		31	
			Brain	0.038 (± 0.024)		24	
			Blood	0.037 (± 0.017)		24	
			Blubber	0.037 (± 0.015)		16	
			Testis	0.35 (± 0.10)		3	
			Ovary	0.84 (± 0.32)		3	
			Skin	0.14 (± 0.03)		5	
			Bone	0.16 (± 0.03)		5	
			Placenta	0.04 (± 0.02)		15	
			Mammary gland	0.46 (± 0.17)		4	
			Milk	0.03 (± 0.04)		10	
		Zn	Muscle	11.4 (± 2.44)		57	
			Pancreas	27.2 (± 5.91)		16	
			Lung	20.7 (± 5.16)		15	
			Heart	26.1 (± 2.75)		15	
			Spleen	21.5 (± 2.25)		12	
			Large intestine	21.1 (± 1.97)		15	
			Stomach, 1st	23.2 (± 3.7)		15	
			Stomach, 2nd	25.3 (± 2.35)		14	
			Diaphragm	44.9 (± 4.07)		15	
			Liver	43.7 (± 14.2)		31	
			Kidney	30.0 (± 4.59)		31	
			Brain	12.6 (± 0.82)		24	
			Blood	3.88 (± 1.05)		24	
			Blubber	5.66 (± 5.9)		16	
			Testis	12.1 (± 0.67)		3	
			Ovary	20.0 (± 0.14)		3	
			Skin	22.7 (± 1.67)		5	
			Bone	40.3 (± 84.3)		5	
			Placenta	18 (± 3.63)		15	
			Mammary gland	20.7 (± 1.99)		4	
			Milk	11.0 (± 3.29)		10	
Order Insectivora Shrew (*Sorex araneus*)	Sweden, coniferous forest	^{137}Cs	Homogenized carcasses (minus skulls and digestive organs)	2580.25 Bq/kg	2.0 – 12,520	64	Masconzoni et al., 1990 (*94*)
European mole (*Talpa europea*)	Netherlands, pasture, heath (smelter contaminated)	Cd	Liver	133.6	25.0 – 234.0		Ma, 1987 (*95*)
			Kidney	160.4	30.0 – 419.0		
		Cu	Liver	25.2	20.0 – 30.0		
			Kidney	27.8	22.0 – 37.0		
		Pb	Liver	14.4	5.0 – 40.0		

(Continued)

Table 1. ***Continued.***

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Range	N	Reference
			Kidney	87.6	8.0 – 438.0		
		Zn	Liver	172.8	111.0 – 244.0		
			Kidney	252.2	105.0 – 449.0		
Order Lagomorpha	Germany[d]	Pb	Liver	13.1[i]		28	Hecht, 1984 (*80*)
Hare (*Lepus cuniculus*)	(contaminated)		Kidney	6.31		27	
			Muscle	0.78		25	
		Cd	Liver	1.94		28	
			Kidney	16.9		27	
			Muscle	0.016		25	
Brown hare (*Lepus europaeus*)	Czechoslovakia[d] (heavily polluted)	Sm	Hair	0.077		33	Paukert and Obrusnik, 1986 (*96*)
		La		0.470			
		Au		0.008			
		Zn		195			
		Cu		11.5			
		As		2.4			
		Se		4.4			
		Cr		2.21			
		Sc		0.141			
		Fe		313			
		Sb		0.08			
		Ce		1.12			
Order Perrisodactyla		Pb					Burrows, 1981 (*6*)
Horse (*Equus equus*)							
Order Rodentia	Sweden, coniferous	^{137}Cs	Homogenized carcasses (minus skulls and digestive organs)	3456.75 Bq/kg	2.0 –32,330	121	Masconzoni et al., 1990 (*94*)
Bank vole (*Clethrionomys glareolus*)	forest						
Field vole (*Microtis agrestis*)	England, sewage farm (contaminated)	Zn	Liver	149		5	Beardsley et al., 1978 (*98*)
			Kidney	108			
			Brain	76			
			Femur	193			
			Remaining carcass	174			
		Cu	Liver	50	40 – 56		
			Kidney	33	21 – 56		
			Brain	20			
			Femur	12			
			Remaining carcass	10			
		Mn	Liver	10			
			Kidney	7			
			Brain	6			
			Femur	4			
			Remaining carcass	4			
		Cd	Liver	5	4 – 9		
			Kidney	8	2 – 14		
			Brain	<0.1			
			Femur	<0.3			
			Remaining carcass	1			
		Pb	Liver	3			
			Kidney	7			
			Brain	4			
			Femur	13	12 – 17		
			Remaining carcass	12	9 – 15		
		Cr	Liver	0.3			
			Kidney	0.5			
			Brain	0.3			
			Femur	<0.8			
			Remaining carcass	5			
Common vole (*Microtis arvalis*)	Czechoslovakia[d]	Sm	Hair	0.040		36	Paukert and Obrusnik, 1986 (*96*)
		La		0.065			
		Au		0.012			
		Zn		197.0			
		Cu		8.69			
		As		2.385			
		Se		0.925			
		Cr		2.245			
		Sc		0.124			
		Fe		293.5			

(Continued)

Table 1. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Concentration, ppm Range	*N*	Reference
		Sb		0.135			
		Ce		0.50			
		Co		0.150			
		Cs		0.077			
Meadow vole (*Microtus pennsylvanicus*)	New York, hazardous waste site					318	Rowley et al., 1983 (*98*)
Muskrat (*Ondatra zibethica*)	S.E. Pennsylvania, stream, marsh, mine, agricultural, and urban effluent	Cd	Liver	0.144		65	Everett and Anthony, 1976 (*99*)
			Kidney	0.528			
		Zn	Liver	47.22		63	
			Bone	175.98			
		Cu	Liver	3.91		64	
			Kidney	2.14			
		Pb	Liver	0.051			
			Bone	1.57			
		Hg	Liver	0.048		63	
Norway rat (*Rattus norvegicus*)	Houston, urban, rural, bayou, prairie	Pb	Muscle	0.06		74	Way and Schroder, 1982 (*100*)[j]
			Bone	18.97		71	
			Liver	1.11		73	
			Kidney	2.28		67	
			Lung	0.40		70	
			Stomach contents	4.07			
			Feces	0.32		58	
		Cd	Muscle	<0.01		74	
			Bone	<0.01		71	
			Liver	0.04		73	
			Kidney	0.14		69	
			Lung	<0.01		33	
			Stomach contents	0.02		39	
			Feces	0.35		59	
Gray squirrel (*Sciurus carolinensis*)	Florida, urban	Hg	Hair	1.1 (± 0.2)	0.07–9.2	66	Jenkins et al., 1980 (*101*)
		^{137}Cs	Muscle	4300 (± 800) pCi/k	250–29,000	46	

ND, not detected.
[a]pCi/kg.
[b]Wet weight.
[c]Samples were collected from 49 roe deer, 1 red deer, 1 ibex, and 1 wild boar.
[d]Habitat not specified.
[e]Dry weight.
[f]Includes outliers.
[g]Pooled sample.
[h]Freeze-dried tissues.
[i]Median values.
[j]Authors propose species as indicator and monitor interchangeably.

Table 2. Species proposed or used as monitors.

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Concentration, ppm Range	*N*	Reference
Order Artiodactyla Family Bovidae	Denmark, farm	Cd	Kidney			81	Anderson and Hansen, 1982 (*102*)
Cattle (*Bos taurus*)	Missouri, farm (contaminated by Pb smelter and highway)	Cd	Hair	1.29[a]		4	Dorn et al. 1974 (*103*)
		Cu		8.26			
		Pb		94.13			
		Zn		104.50			
	Australia, terrestrial, arid	Organochlorine (DDE)	Fat	0.025	0.01 – 0.04	4	Best, 1973 (*24*)
(*Bos indicus*)	India, village (contaminated by Pb processing)	Pb	Milk		0.05 – 0.15	3	Bhat and Krishnamachari, 1980 (*104*)
			Dung		4.7 – 38	7	
			Soil		24 – 183	3	
			Stream		<75		
		Cu	Milk		0.008 – 0.01	3	
			Dung		0.02 – 0.24	7	

(Continued)

Table 2. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Concentration, ppm Range	*N*	Reference
			Soil		0.25 – 1.2	3	
		Zn	Milk		0.02 – 0.06	3	
			Dung		0.65 – 3.1	7	
			Soil		4.0 – 11.0	3	
Water buffalo (*Bubalus bubalus*)	Australia, terrestrial, tropical	Organochlorine	Fat			25	Best, 1973
Family Cervidae	Norway, terrestrial[b]	Cd	Liver[c]	0.6 (± 0.5)	< 0.1 – 3.4	775	Fröslie et al., 1986 (*105*)
Moose (*Alces alces*)							
			Kidney	2.9 (± 2.6)	0.1 – 19.0	796	
	Sweden, terrestrial[b]	Cd	Liver	0.45[d]	0.1 – 0.9	9	Frank, 1986 (*7*)
			Kidney	1.7	1.3 – 7.0		
Roe deer (*Capreolus capreolus*)	Sweden, terrestrial[b]	Cd	Liver	0.48[d]	0.02 – 1.7	25	Frank, 1986 (*7*)
			Kidney	5.2	0.07 – 8.6		
	Norway, terrestrial[b]	Cd	Liver	0.4 (± 0.5)	< 0.1 – 2.5	77	Fröslie et al., 1986 (*105*)
			Kidney	2.8 (± 2.8)	0.2 – 4.0		
	Germany, forest	Pb, Cd, Hg, As	Kidney				Kleiminger, 1983 (*106*)
Red deer (*Cervus elaphus*)	Norway, terrestrial[b]	Cd	Liver	0.1 (± 0.08)		17	Fröslie et al., 1986 (*105*)
			Kidney	0.8 (± 0.8)		18	
	The Netherlands[b]	Cd	Kidney (cortex)	0.03 (± 0.031)		51	Holterman et al., 1984 (*54*)
		Zn		0.51 (± 0.37)			
Reindeer (*Rangifer tarandus*)	Norway, terrestrial[b]	Cd	Liver	1.1 (± 0.7)	0.1 – 4.6	248	Fröslie et al., 1986 (*105*)
			Kidney	5.7 (± 5.2)	0.3 – 34.0	204	
	Sweden, terrestrial[b]	Cd	Liver	0.1[d]	0.09 – 0.15	3	Frank, 1986 (*7*)
			Kidney	0.45	0.37 – 1.3		
Order Carnivora Suborder Pinnipedia	U.S. Pacific Coast, island, ocean	Total DDT + PCBs[e]	Blubber	495.54	6.8 – 2,350.0	13	Anas, 1974 (*107*)
Harbor seal (*Phoca vitulina*)	Nova Scotia, ocean	Hg	Fur	1.8		1	Freeman and Horne, 1973 (*108*)
			Claws	1.8			
			Liver	0.99			
			Kidney	0.67			
			Muscle	0.55			
			Heart	0.23			
			Stomach	0.22			
			Brain	0.17			
			Blubber	0.076			
			Gonad	0.31			
			Spleen	0.24			
			Eye	0.095			
			Lung	0.17			
			Pancreas	0.27			
			Large intestine	0.17			
			Small intestine	0.26			
Harp seal (*Phoca groenlandica*)	Northwest Atlantic, ocean	Hg	Blood	0.08[d]	0.01 – 0.15	144	Ronald et al., 1984 (*109*)
			Brain	0.14	0.07 – 0.21	166	
			Kidney	1.25	0.36 – 2.14	236	
			Liver	7.0	0.70 – 13.3	215	
			Muscle	0.31	0.12 – 0.49	225	
		Se	Blood	0.93	0.55 – 1.8	7	
			Brain	0.51	0.31 – 0.71	31	
			Kidney	3.12	1.84 – 4.4	62	
			Liver	4.37	1.01 – 7.73	89	
			Muscle	0.54	0.4 – 0.68	50	
		Cu	Blood	2.94	0.86 – 5.01	143	
			Brain	7.49	3.67 – 11.3	168	
			Kidney	8.85	4.51 – 13.2	232	
			Liver	20.95	11.2 – 30.7	216	
			Muscle	2.73	1.57 – 3.89	225	
		Cd	Blood	0.22	0.01 – 0.42	144	
			Brain	0.15	0.01 – 0.28	169	
			Kidney	19.48	0.15 – 38.8	232	

(Continued)

Table 2. ***Continued.***

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm: Mean (± SD)	Concentration, ppm: Range	*N*	Reference
			Liver	6.03	0.05 – 12.0	216	
			Muscle	0.25	0.01 – 0.48	225	
		Pb	Blood	0.16	0.02 – 0.30	146	
			Brain	0.42	0.08 – 0.75	159	
			Kidney	0.10	0.01 – 0.19	232	
			Liver	0.40	0.02 – 0.77	216	
			Muscle	0.12	0.02 – 0.22	227	
	Nova Scotia, ocean	Hg[f] (adults)	Fur	3.2 (± 0.25)	2.1 – 3.8	10	Freeman and Horne, 1973 (*108*)
			Claws	3.7 (± 0.41)	2.2 – 5.4		
			Liver	4.6 (± 0.89)	1.9 – 9.4		
			Flipper	0.48 (± 0.054)	0.27 – 0.84		
			Muscle (dorsal)	0.46(± 0.044)	0.28 – 0.7		
			Muscle (light)	0.31 (± 0.044)	0.23 – 0.39		
			Heart	0.28 (± 0.031)	0.13 – 0.43		
			Blubber	0.14 (± 0)	0.063 – 0.23		
		Hg (pups)	Fur	1.7 (± 0.26)	0.63 – 3.6	10	
			Claws	1.8 (± 0.27)	0.8 – 3.6		
			Liver	0.46 (± 0.054)	0.18 – 0.83		
			Flipper	0.23 (± 0)	0.16 – 0.32		
			Muscle (dorsal)	0.22 (± 0)	0.14 – 0.29		
			Heart	0.17 (± 0)	0.11 – 0.23		
			Brain	0.15 (± 0)	0.11 – 0.18		
			Stomach	0.13 (± 0)	0.089 – 0.17		
			Stomach contents	0.088 (± 0)	0.04 – 0.17		
			Kidney	0.35 (± 0)	0.25 – 0.51		
Ringed seal (*Phoca hispida*)	Nova Scotia ocean	Hg	Claw	1.9		14	Freeman and Horne, 1973 (*108*)
Bearded seal (*Erignathus barbatus*)	Nova Scotia, ocean	Hg	Claw	1.13		9	Freeman and Horne, 1973 (*108*)
Gray seal (*Halichoerus grypus*)	Nova Scotia, ocean	Hg	Fur	5.98	1.4 – 16.0	6	Freeman and Horne, 1973 (*108*)
			Claw	6.56	3.2 – 9.8		
			Liver	13.98	2.8 – 30.0		
			Kidney	3.25	1.5 – 5.7		
			Flipper	0.925	0.91 – 0.94	2	
			Muscle (dorsal)	1.04	0.58 – 1.6	6	
			Heart	0.49	0.28 – 0.75		
			Gonad	0.36	0.18 – 0.6		
			Blubber	0.075	0.036 – 0.11		
			Brain	0.33	0.19 – 0.45		
Family Canidae Dog (*Canis familiaris*)	Illinois, suburban	Pb (normal)	Blood	7.8 (± 7.3)	0 – 29.0	89	Thomas et al., 1975 (*110*)
		Pb (city pound)	Blood	26.2 (± 15.7)	0 – 72.0	50	
		Pb (low-income families)	Blood	17.2 (± 17.4)	0 – 80.0	98	
	Tasmania, urban	Pb	Blood	6.4 μg/100 mL		206	Bloom et al., 1976 (*111*)
	North Carolina lab	Leptophos				10	Soliman, 1983 (*112*)
European red fox (*Vulpes vulpes*)	Sweden, terrestrial[b]	Cd	Liver	0.16[d]	0.04 – 1.5	4	Frank, 1986 (*7*)
			Kidney	0.43	0.16 – 5.6		
	Australia, terrestrial, arid	DDE	Fat	0.03		2	Best, 1973 (*24*)
Family Felidae		Hg					Wren, 1986 (*71*)
Cat (*Felis catus*)	Tasmania, urban	Pb	Blood	5.2 μg/100 mL		26	Bloom et al., 1976 (*111*)
	Australia, terrestrial, arid	DDE	Fat	0.04	0.01 – 0.07	2	Best, 1973 (*24*)
Family Mustelidae Mink (*Mustela vision*)	Michigan, laboratory	TCDD				16	Hochstein et al., 1988 (*113*)
	Sweden, terrestrial[b]	Cd	Liver	0.08[d]	0.03 – 0.24	6	Frank, 1986 (*7*)
			Kidney	0.20	0.07 – 0.56		
		Hg					Wren, 1986 (*71*)
River otter (*Lutra canadensis*)	Virginia[b]	Cd (1979–80)	Liver[a]	0.09 (± 0.01) mg/g	< 0.04 – 0.99	226	Anderson-Bledsoe and Scanlon, 1983 (*114*)
			Kidney	0.61 (± 0.09)	< 0.04 – 14.09	221	

(Continued)

Table 2. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Range	N	Reference
			Bone	<0.04		198	
		Pb (1979–80)	Liver	1.40 (± 0.62)	<0.4 – 55.89	226	
			Kidney	0.81 (± 0.07)	<0.4 – 6.0	221	
			Bone	1.41 (± 0.22)	<0.4 – 35.16	198	
		Zn (1979–80)	Liver	62.63 (± 2.17)	<0.08 – 235.78	226	
			Kidney	78.91 (± 4.88)	<0.08 – 564.34	221	
			Bone	179.13 (± 9.49)	<0.08 – 822.93	198	
		Cu (1979–80)	Liver	13.92 (± 1.48)	<0.16 – 211.0	226	
			Kidney	6.16 (± 0.59)	<0.16 – 80.15	221	
			Bone	0.13 (± 0.04)	<0.16 – 5.69	198	
		Cd (1980–81)	Liver	0.17 (± 0.07)	<0.04 – 1.58	131	
			Kidney	0.37 (± 0.04)	<0.04 – 3.10	169	
			Bone	<0.04	<0.04 – 0.27	78	
		Pb (1980–81)	Liver	3.43 (± 0.37)	<0.4 –16.97	131	
			Kidney	1.68 (± 0.15)	<0.4 – 9.75	169	
			Bone	5.31 (± 0.63)	<0.4 – 18.13	78	
		Zn (1980–81)	Liver	154.38 (± 11.82)	<0.08 – 683.85	131	
			Kidney	176 (± 9.93)	21.53 – 801.59	169	
			Bone	138.71 (± 14.39)	<0.08 – 587.05	78	
		Cu (1980–81)	Liver	9.96 (± 0.78)	<0.16 – 52.18	131	
			Kidney	3.22 (± 0.23)	<0.16 – 16.13	169	
			Bone			78	
		Hg					Wren, 1986 (*71*)
River otter (*Lutra lutra*)	Sweden, terrestrial[b]	Cd	Liver[c]	0.35[d]	0.26 – 0.82	3	Frank, 1986 (*7*)
			Kidney	0.96	0.9 – 2.4		
Marten (*Martes martes*)			Liver	0.5	0.3 –0.5	3	
			Kidney	2.1	2.0 – 2.4		
European badger (*Meles meles*)			Liver	1.8	0.27 – 3.3	4	
			Kidney	8.8	1.9 – 8.8		
Family Procyonidae Raccoon (*Procyon lotor*)	Kansas, aquatic	Chlordane	Fat	2.4		1	Layher et al., 1987 (*116*)
		p,p'-DDE	Fat[g]	0.05	0.046 – 0.055	2	
		HCB		0.073	0.012 – 0.44		
		HE		0.192	0.043 – 0.65		
Order Insectivora West European hedgehog (*Erinaceus europaeus*)	Sweden, terrestrial[b]	Cd	Liver	0.72[d]	0.33 – 1.3	4	Frank, 1986 (*7*)
			Kidney	2.7	0.86 – 4.2		
Order Lagomorpha Arctic hare (*Lepus timidus*)	Sweden, terrestrial[b]	Cd	Liver	0.34[d]	0.03 – 0.53	5	Frank, 1986 (*7*)
			Kidney	2.6	0.09 – 5.3		
Brown hare (*Lepus europaeus*)	Sweden, terrestrial[b]	Cd	Liver	0.36[d]	0.02 – 0.93	6	Frank, 1989 (*7*)
			Kidney	3.1	0.06 – 6.0		
	Germany, forest	Pb, Cd, Hg, As	Kidney				Kleiminger, 1983 (*107*)
Rabbit (*Oryctolagus cuniculus*)	Spain, stabilized sands, marshes	α-HCH	Liver	0.016	0.01 – 0.05	5	Hernandez et al., 1985 (*29*)
			Muscle				
		δ-HCH	Liver	0.017	0.01 – 0.02		
			Muscle				
		DDE	Liver	0.073	0.05 – 0.11		
			Muscle	0.037	0.02 – 0.07		
		DDT	Liver	0.023	0.02 – 0.03		
			Muscle	0.007	ND – 0.01		
		PCBs	Liver	0.111	0.07 – 0.17		
			Muscle	0.059	0.04 – 0.08		
		Hg	Liver	0.11	0.07 – 0.16		
			Muscle	0.10	0.05 – 0.16		
		Cd	Liver	0.19	0.16 – 0.22		
			Muscle	0.07	0.04 – 0.11		
		Pb	Liver	1.34	1.25 – 1.43		
			Muscle	0.78	0.50 – 2.46		
		Cu	Liver	5.76	5.14 – 6.46		
			Muscle	1.08	0.68 – 1.86		
		Zn	Liver	61.08	54.05 – 69.02		
			Muscle	13.44	9.4 – 22.9		

(Continued)

Table 2. *Continued.*

Species	Location of study and habitats assessed	Toxicants	Tissues or environmental samples	Concentration, ppm Mean (± SD)	Range	N	Reference
Rabbit[h]	Italy, small farms	TCDD, ng/g	Liver	53.38	0.32–633.0	309	Fanelli et al., 1980 (*8*)
Order Perrisodactyla Horse (*Equus equus*)	Poland[b]	Hg	Kidney	0.237 (± 0.057)	0.08 - 0.59	96	Juszkiewicz and Szprengier, 1974 (*116*)
	The Netherlands[b]	Cd	Kidney	0.31 (± 0.21) nmole/kg		63	Holterman et al., 1984 (*54*)
		Zn	Kidney (cortex)	0.63 (± 0.17)			
Order Rodentia Bank vole (*Clethrionomys glareolus*)	Poland, forest born, laboratory study	Pb					Zakrzewska, 1988 (*117*)
White-footed mouse (*Peromyscus leucopus*)	Pennsylvania, rural captured, laboratory study	Aroclor 1254					Linzey, 1987 (*118*)
Cotton rat (*Sigmodon hispidus*)	Oklahoma, toxic waste disposal site		Liver			22	Elangbam et al., 1989 (*119*)

ND, not detected.
[a]Dry weight.
[b]Habitat not specified.
[c]Wet weight.
[d]Median values.
[e]DDD + DDE = DDT.
[f]Levels of MeHg were determined for some individuals in this study.
[g]Composite sample (internal parietal and peritoneal fat).
[h]Species not specified.

suggesting similar pathobiological effects in mink and humans. The mink might also be considered to assess interactive or synergistic effects between PCB and other toxicants in diets. PCB-treated mink have been shown to have increased accumulation of cadmium (*66*), and dietary PCBs and methylmercury have been shown to have a synergistic negative effect on the survival of offspring of treated females (*62*). The mink might serve as a sentinel where similar effects are of interest in pregnant women.

A final example might be made relating to human exposure to methymercury. Humans are known to accumulate body burdens of mercury from eating fish (*67*), and fish and shellfish are considered the only regular dietary source of practical importance (*68*). In considering a sentinel for this situation, a piscivore is then needed. The river otter (*Lutra canadensis*) might be a good choice as a wild mammal, and the cat a good domestic one. Methylmercury intoxication is known to produce similar clinical neurological signs in the otter (*69*), cat (*18*), and humans (*70*). River otters are known to be sensitive biomonitors of environmental mercury availability (*71*), and the use of the cat as a sensitive mercury sentinel has already been discussed. Perhaps most importantly, the gross and histopathologic changes (cerebral cortical atrophy, neuronal degeneration, astrogliosis, etc.) of methylmercury intoxication in humans (*44*) are duplicated in the river otter (*72*) and cat (*73,74*). By using two sentinels simultaneously, one could assess not only the usefulness of each species in the field, but the way in which quantitative differences in exposure or other factors affect their predictive value for human effects. In addition, descriptive epidemiologic information might be obtained that could define hypotheses and cohorts for future analytical research.

As stated before, these examples are not recommendations, nor are they intended to be conclusive. Indeed, it seems clear that no one sentinel mammal can encompass all situations when assessing the potential effects of toxic environmental contamination on human health. While the potential impact of sentinel use in the field of environmental health is enormous and still at a seminal stage, future investigators need to be careful to choose sentinels based on well-defined research questions and confine any conclusions drawn from results to the focus of the particular problem and specific subpopulation the sentinel was chosen to assess. It is hoped that the limited scope of individual studies can be combined with, and interpreted in light of, the work of others to turn this potential into tangible knowledge that will benefit not only humans, but also the other creatures that share our world.

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